

# Gluon-decay cascade in AA collisions at the LHC and saturation

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We extract the energy-dependence of the gluon-jet decay cascade from  $e^+e^-$  annihilation data and show that this energy-dependence has power-law behavior for the average transverse momentum of jet bigger than 1 GeV. We show that the observed different power-law energy-dependence of hadron multiplicity in AA compared to pp collisions at the LHC is due to the enhanced gluon-decay effect before hadronization. This effect is more important for AA collisions where the saturation scale is larger than 1 GeV. Here we confront our published predictions in arXiv:1102.2385 for the rapidity distribution of the charged hadron production with the recently released data from the CMS collaboration in AA collisions and show that our predictions is in perfect agreement with the data.

## 1 Introduction

One of the most unexpected new feature of the LHC data has been the very different power-law energy behavior of the charged hadron multiplicities in AA compared to pp collisions [1, 2]. There have been several approaches to address the above problem [3, 4, 5, 6]. This is closely related to the open problem of entropy production at the early stage of heavy-ion collisions (Mini Bangs).

In the following, we provide a simple explanation of this observation and confront our published predictions [3] with the recently released data from the LHC [2] for the rapidity distribution of the charged hadron production.

## 2 Main formalism and predictions

In the Color Glass Condensate (CGC)/saturation based approaches (for a recent review see Ref. [7]), the hadron production may be divided in two stages: production of gluons and subsequently the decay of gluon-jet (or mini-jet) into hadrons. Therefore, the multiplicity of the produced hadrons at pseudo-rapidity  $\eta$  can be calculated as a convolution of these two stages (see Fig. 1):

$$\frac{dN_h}{d\eta d^2p_T} \propto \frac{dN^{Gluon}}{dy d^2p_T} \otimes N_h^{Gluon}(E_{jet}), \quad (1)$$

$$\frac{dN_h}{d\eta} \propto \sigma_s Q_s^2 \times N_h^{Gluon}(Q_s), \quad (2)$$

where  $\frac{dN^{Gluon}}{dy d^2p_T}$  gives the gluon jet production yield at rapidity  $y$  (in pp or AA collisions) computable in the  $k_T$  factorization scheme [3, 8, 10]. The second term  $N_h^{Gluon}$  is the average multiplicity of hadrons in the gluon jet with a jet energy  $E_{jet}$  computable in the Modified Leading Logarithmic Approximation (MLLA) scheme [8, 11]. The symbol  $\otimes$  indicates a convolution, that is, integrals over variables with possible weight factors included [3].

The greatest simplicity of the CGC approach is the fact that all complexity of infinite-body problem at very high energy (or small  $x$ ) shall be reduced into a one scale problem, with a hard saturation scale  $Q_s$  as the only dimensional relevant scale at which nonlinear gluons recombination effects start to become important. In this framework, the secondary hadrons are originated from the decay of gluon mini-jets with the transverse momentum equal to the saturation scale  $Q_s$  [3, 8, 9]. Then Eq. (2) up to a possible logarithmic correction, can be readily obtained by a dimensionality argument where  $\sigma_s$  is the effective area of interaction.

Notice that the  $k_T$  factorization has been proven at the leading  $\log(1/x)$  approximation for scatterings of a dilute system on a dense one (such as proton-nucleus collisions) and includes BFKL type gluon emissions (with gluon fusion effects) between the projectile and target, and also gluon radiations from the produced gluons [10]. However, the other contribution of the gluon decay, before hadronization, stems from the kinematic region outside the BFKL emission regime where both emitted gluons are collinear to the emitter [3]. In this kinematic region, the angle between the gluon (quark) and the decay gluon is small and the main contribution of gluon-decay has an opposite angular ordering to the BFKL type gluon emissions. The later kinematic region has been traditionally studied within a different resummation scheme, the so-called MLLA where it

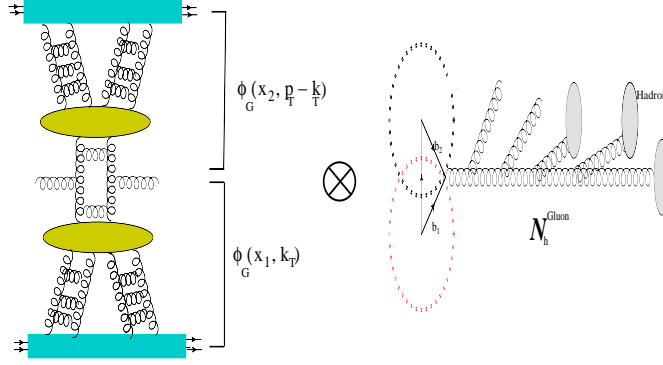


Figure 1: The corresponding diagram to the factorization given in Eq. (1). In the  $k_T$  factorization, the gluon production can be calculated as a convolution of two unintegrated gluon density  $\phi_G$  of the projectile and target [10].

contains systematically next-to-leading logarithmic corrections and incorporates single and double-logarithmic effects in the development of parton cascades [11]. Notice that the gluon decay effect incorporated within these two resummation schemes have different kinematics [3, 10, 11].

It is well-known that the gluon decay probability can be factorized from the rest of cross-section in  $e^+e^- \rightarrow q\bar{q}g$  reaction [11]. This is in a sense, the essence of the factorization given in Eq. (1). One may extract information about the gluon-decay stage in the MLLA region from gluon jet data in  $e^+e^-$  collisions. In order to obtain the energy dependence of the function  $N_h^{Gluon}$ , we use directly experimental data for  $N_h^{Gluon}(E_{jet})$  in  $e^+e^-$  annihilation [3]. One can see from Fig. 2 that  $N_h^{Gluon}$  is constant at about  $E_{jet} < 1$  GeV and it grows as a power of  $E_{jet}$  at higher energies. From the available  $e^+e^-$  collisions data shown in Fig. 2, we found that the energy-dependence of the mean charged particle multiplicity of gluon-jet can be approximately described by

$$\langle N_h^{Gluon} \rangle \propto E_{jet}^\delta, \quad \text{with } \delta = 0.6 \div 0.7 \quad \text{for } E_{jet} \geq 0.85 \div 1 \text{ GeV}. \quad (3)$$

It is essential to stress again that such behavior also follows from the theoretical estimates in the 3NLO pQCD in the MLLA scheme [11]. Now, using Eqs. (2,3) and assuming the typical energy of the gluon jet to be of the order of average saturation scale, we obtain,

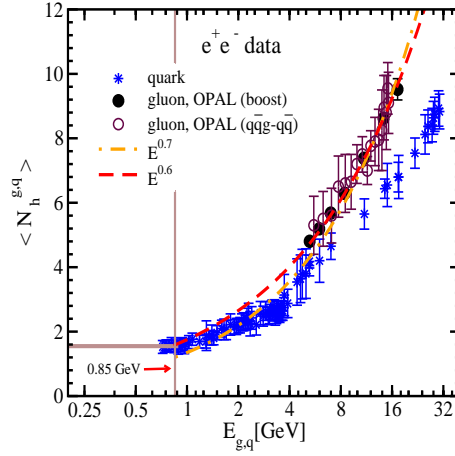


Figure 2: The mean charged hadron multiplicity of unbiased gluon  $N_h^g$  and quark  $N_h^q$  jets in  $e^+e^-$  annihilation, as a function of the jet energy. The plot is taken from [3].

$$\frac{dN_h}{d\eta}(pp) \propto Q_s^2 \propto s^{\lambda/2} = s^{0.11}, \quad (4)$$

$$\frac{dN_h}{d\eta}(AA) \propto Q_s^2 \times (E_{jet} \propto Q_s)^{0.65} \propto s^{\lambda/2+0.65 \times \lambda/4} = s^{0.145}, \quad (5)$$

where  $s$  is the center-of-mass energy squared per nucleon pair and  $\lambda$  is free parameter to be fixed with other experiments like DIS at HERA. In the above we assumed that the saturation scale for pp collisions is  $Q_s < 1$  GeV and for AA collisions we have  $Q_s > 1$  GeV. We take for the parameter  $\delta$ , the average value  $\bar{\delta} = 0.65$  from Eq. (3). In Eq. (4), the average value of  $\lambda \approx 0.22$  in the the effective saturation scale for pp collisions can be obtained from  $k_T$  factorization results given in Ref. [8]. Then, the power-law behavior given in Eq. (5) for AA collisions comes naturally without any extra freedom. The simple Eqs. (4,5) are enough to describe energy-dependence of all existing data on hadron multiplicity from RHIC to the LHC, see Fig. 3 (right). Indeed the full calculation [3] (shown by orange line in Fig. 3) based on the factorization shown in Fig. 1, agrees with the above argument based on the dimensionality. It is seen from Eqs. (3,5) that the  $k_T$  factorization accounts for the most energy-dependence of the hadron multiplicity  $s^{0.11}$ , while the MLLA gluon-decay cascade (extracted from  $e^+e^-$  annihilation data) brings only about  $s^{0.036}$  extra effect. Notice that in the above we assumed that the atomic

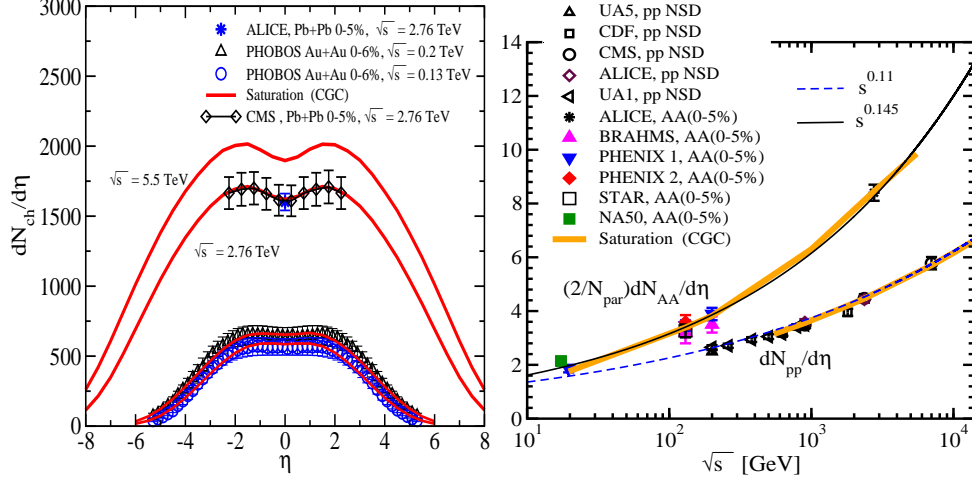


Figure 3: Right: The energy behavior of charged particle pseudo-rapidity per participant pair for central AA and non-singlet diffractive pp collisions. The right panel plot is taken from Ref. [3]. Left: Pseudo-rapidity distribution of charged particles produced at RHIC and the LHC. The experimental data from the LHC are from [2, 1].

number or  $A$  (size of nuclei) dependence of the saturation scale is factorizable from energy. This assumption can be simply justified from the observation that the centrality dependence of the multiplicity at the LHC is very similar to RHIC up to an overall scale, see Fig. 4. This means that the energy and centrality or  $A$  dependence of multiplicity (and saturation scale) can be scaled out, in agreement with our assumption. Therefore, data seems to rule out any extra energy dependence to be generated due to the geometry and the centrality of collisions. In Fig. 3, we compare our published prediction [3] for the rapidity distribution of charged hadrons coming from the full calculation with the recent CMS data [2]. It is seen in Fig. 3 that our predictions is in excellent agreement with data. Our prediction for  $dN_{AA}/d\eta$  at midrapidity for 0 – 5% Pb+Pb collisions at 5.5 TeV is  $1897 \pm 133$  [3]. We also show in Fig. 3 our prediction for the rapidity distribution of charged hadrons multiplicity for Pb+Pb collisions at 5.5 TeV [3].

In Fig. 4 (right), we show  $(2/N_{par})(dN_{AA}/d\eta)$  at midrapidity (where  $N_{par}$  is the number of participant for a given centrality) has the scaling property at different energies. Notice that one can already observe similar scaling property at RHIC, namely  $dN_{AA}/d\eta$

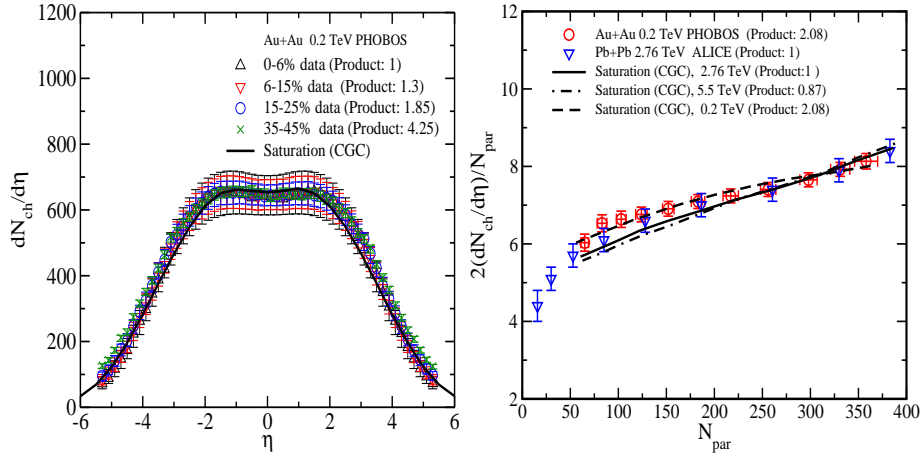


Figure 4: Right: The scaled pseudo-rapidity density as a function of number of participant at midrapidity for AA collisions at various energies. Left: The pseudo-rapidity distribution at RHIC 0.2 TeV at different centralities. The plots are taken from Ref. [3].

at fixed energy but different centralities falls into a single curve upto a normalization factor, see Fig. 4 (left). Both scaling properties shown in Fig. 4 can be easily understood within the CGC picture and follows from simple Eq. (2). We expect that the centrality-scaling for  $dN_{AA}/d\eta$  at a fixed energy will be also valid at the LHC. We predict that  $(2/N_{par})(dN_{AA}/d\eta)$  for 5.5 TeV AA collisions at midrapidity to be about  $\frac{1}{0.87 \pm 0.06}$  times bigger than the corresponding one at 2.76 TeV.

In Fig. 5 (right) we show the experimental data from the STAR collaboration [12] for  $\langle p_T \rangle / \sqrt{(dN^\pi/d\eta)/S_T}$  as a function of centrality where  $\langle p_T \rangle$  is the average transverse momentum and  $S_T$  is the overlap area between the colliding nuclei in the transverse plane. In our approach, we have  $\langle p_T \rangle / \sqrt{(dN/d\eta)/S_T} \sim \frac{1}{n\sqrt{n}}$  where  $n \sim N_h^{gluon}$  for  $Q_s > 0.85 \div 1$  GeV corresponding to the excess of charged hadron production in the presence of jet-decay effects. It is seen from Fig. 5 that the ratio  $\langle p_T \rangle / \sqrt{(dN/d\eta)/S_T}$  at RHIC Au+Au collisions decreases for more central collisions and higher energies in accordance with our model and in contrast to the KLN type approach [13, 5]. We expect that the ratio  $\langle p_T \rangle / \sqrt{(dN/d\eta)/S_T}$  will be further suppressed at the LHC compared to RHIC, see Fig. 5. Moreover, in the KLN type approaches [13] we have  $\langle p_T \rangle \sim x$  where  $x = \sqrt{(dN/d\eta)/S_T}$  while in our approach we have  $\langle p_T \rangle \sim x^{0.264}$  for the case that the

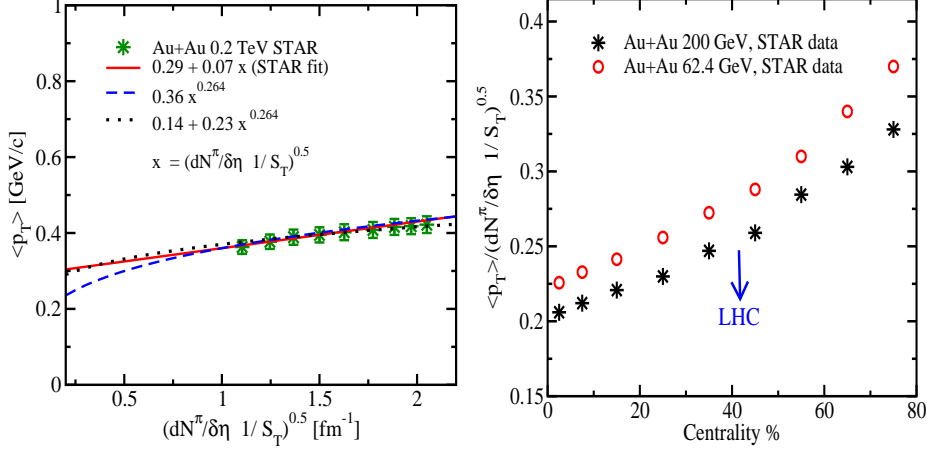


Figure 5: Right: The ratio  $\langle p_T \rangle / \sqrt{(dN^\pi/d\eta)/S_T}$  at various centralities at RHIC. The data was constructed from three experimental measurements, the average transverse momentum  $\langle p_T \rangle$  of  $\pi^-$ ,  $dN^\pi/d\eta$  and  $S_T$  [12]. Left: Average transverse momenta as a function of  $\sqrt{(dN^\pi/d\eta)/\sigma_s}$  at RHIC. The experimental data are from [12].

saturation scale is  $Q_s > 0.85 \div 1$  GeV. In Fig. 5 (left) we show the average transverse momenta as a function of  $\sqrt{(dN/d\eta)/S_T}$ . The STAR collaboration [12] has found that the experimental data for the charged pion at different centralities can be described by  $\langle p_T \rangle \approx p_0 + 0.07x$  where the constant  $p_0 = 0.29$  GeV was obtained from a fit and may be interpreted as primordial transverse momentum. In Fig. 5, we also show that a fit driven by our approach prefers a smaller primordial transverse momentum of about pion mass  $p_0 \sim 0.14$  GeV (or even  $p_0 \sim 0$ ) and it reasonably describes the same data. Notice that at small multiplicity for very peripheral collisions at RHIC energy entire saturation formulation is questionable.

To conclude: we extracted the energy-dependence of the gluon-jet decay cascade from  $e^+e^-$  annihilation data. We showed that the energy-dependence of about  $s^{0.036}$  due to the gluon-decay cascade (when the average transverse momentum of the jet becomes about or bigger than 1 GeV) is exactly what explains the different power-law energy-dependence of hadron multiplicity in AA compared to pp collisions at the LHC. This effect is more important for AA collisions where the saturation scale is larger and gives rise to an extra contribution about 20 – 25% to the multiplicity in AA collisions at the LHC. On the

theory side, this emphasizes on the importance of higher order corrections beyond the leading log approximation in the  $k_T$  factorization, and on general, this also gives rise to the outstanding problem that how the fragmentation processes can be accommodated within the CGC/saturation framework.

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